DOI: 10.1111/1475-6773.13706

RESEARCH ARTICLE

HSR Health Services Research

Patterns of adoption of robotic radical prostatectomy in the United States and England

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Abstract

Objectives: To compare patterns of technological adoption of minimally invasive surgery for radical prostatectomy across the United States and England.

Data Sources: We examine radical prostatectomy in the United States and England between 2005 and 2017, using de-identified administrative claims data from the OptumLabs Data Warehouse in the United States and the Hospital Episodes Statistics in England.

Study Design: We conducted a longitudinal analysis of robotic, laparoscopic, and open surgery for radical prostatectomy. We compared the trends of adoption over time within and across countries. Next, we explored whether differential adoption patterns in the two health systems are associated with differences in volumes and patient characteristics. Finally, we explored the relationship between these adoption patterns and length of stay, 30-day readmission, and urology follow-up visits.

Data Collection: Open, laparoscopic, and robotic radical prostatectomies are identified using Office of Population Censuses and Surveys Classification of Interventions and Procedures (OPCS) codes in England and International Classification of Diseases ninth revision (ICD9), ICD10, and Current Procedural Terminology (CPT) codes in the United States.

Principal Findings: We identified 66,879 radical prostatectomies in England and 79,358 in the United States during 2005–2017. In both countries, open surgery dominates until 2009, where it is overtaken by minimally invasive surgery. The adoption of robotic surgery is faster in the United States. The adoption rates and, as a result, the observed centralization of volume, have been different across countries. In both countries, patients undergoing radical prostatectomies are older and have more comorbidities. Minimally invasive techniques show decreased length of stay and 30-day readmissions compared to open surgery. In the United States, robotic approaches were associated with lower length of stay and readmissions when compared to laparoscopic.

Conclusions: Robotic surgery has become the standard approach for radical proctectomy in the United States and England, showing decreased length of stay and in 30-day readmissions compared to open surgery. Adoption rates and specialization differ across countries, likely a product of differences in cost-containment efforts.

KEYWORDS
administrative data uses, health care organizations and systems, health economics, hospitals, surgery, technology adoption/diffusion/use

What is known on this topic

- Numerous studies have explored the adoption of technology within health systems, but few studies have explored the adoption of the same technology across systems.
- Little is known about the factors associated with the adoption of minimally invasive surgical techniques and robotic surgery in particular.

What this study adds

- The initial adoption of robotic radical prostatectomy was faster in the United States as compared to England.
- Differences in adoption patterns within the two countries seem to influence the centralization of surgical volume across providers.
- The robotic approach has become the standard of care for radical prostatectomy in both countries. Robotic procedures are associated with improvements in length of stay and readmissions relative to open surgery in both countries but only show significant reductions in length of stay and readmissions relative to laparoscopic surgery in the United States.

1 | INTRODUCTION

Rapid advances in medical innovation over the past decades have led to an increase in the range of alternatives for the diagnosis and treatment of disease.[1-4] While these technological advances have been shown to be beneficial to care and improve outcomes, they are not always cost-effective.[1,2,5] Indeed, some of the growth in health care spending across high-income countries is attributed to medical innovation.[5-8] As such, policy makers across health systems have attempted to regulate technological diffusion, through the use of economic and regulatory instruments.[9-11] However, little is known about how new technologies diffuse across systems with different approaches to cost containment.

One of the recent technological developments in the area of surgery has been the introduction of minimally invasive techniques, including laparoscopic and robotic surgery. While the introduction of laparoscopic surgery has predated robotic techniques, they both confer similar patient benefits such as improved patient outcomes and faster operating and recovery times.[12] However, the newer robotic techniques require a higher initial investment to purchase the robot and carry high maintenance costs. Across a spectrum of surgical conditions, laparoscopic techniques have already been adopted as the standard of care (i.e., cholecystectomy). However, for some procedures, such as radical prostatectomy, robotic and laparoscopic adoption has come more recently and in parallel. As minimally invasive techniques become more established within systems, we can examine how they diffuse across health systems and whether we see differential uptake of the higher cost procedure (robotic) in health systems with stricter cost-containment policies. This comparative lens may offer important insights into the factors that influence technological adoption within health systems.

In this study, we explore the differential uptake of laparoscopic and robotic surgery for radical prostatectomy compared to open surgery over the past 13 years in two countries, England and the United States, with notably different cost-containment approaches. In England, prostatectomies provided on the National Health Service (NHS) are reimbursed based on fixed prices in hospitals operating under global budgets, while in the United States, hospitals providing proctectomies do not operate under budgets and are reimbursed by multiple insurers with variable prices. The case of robotic-assisted prostatectomy is of special relevance, given its widespread adoption, despite the high-fixed costs associated with it and the lack of evidence of its clinical superiority.[12,13] Using the Hospital Episode Statistics (HES) data from the English NHS and de-identified administrative claims data from the OptumLabs Data Warehouse (OLDW) in the United States,[14] we explored three questions, (1) Do we see different rates of adoption of robotic surgery for prostatectomy in England and the United States? (2) Do we see differences in practice associated with differential uptake of this technology? and (3) Are different adoption patterns associated with improvements in key surgical outcomes such as length of stay (LoS), 30-day readmission, and the number of urology follow-up visits?

2 | METHODS

2.1 | Data

To examine the uptake of robotic surgery in England, we used HES, an administrative dataset that records all in-hospital admissions in the English NHS. For the United States, we used de-identified administrative claims data from the OLDW,[14] which includes longitudinal health information on enrollees with health coverage from commercial and Medicare Advantage (MA) plans. These data represent a diverse mixture of ages, race/ethnicities, and geographical regions, which are similar to the characteristics of the national US population.[15]

From both datasets, we extracted all admissions related to radical prostatectomies between 2005 and 2017 and disaggregated them by type of approach as follows: open, laparoscopic, and robotic. In England, the admissions were identified by extracting all patients with a prostatectomy procedure code as their main operation, using the Office of Population Censuses and Surveys Classification of Interventions and Procedures (OPCS-4) codes. In the United States, admissions were identified using ICD9, ICD10 Procedure Coding System (PCS), and the Current Procedural Terminology (CPT) codes (Appendix Table A1). Emergency and elective admissions were included for each country as it was not possible to distinguish the admission type in the US data. In England, 99.5% of procedures were elective. In the US data, any admission not linked to a hospital was excluded (7155 patients, 8.2% of the sample). For 2112 patients undergoing a minimally invasive procedure, we could not differentiate type of procedure. We excluded these patients when doing any analysis that required a distinction between robotic and laparoscopic surgery.

Appendix Table A2 shows the yearly prostatectomy volume in the OLDW, relative to a representative sample of national volumes as measured by the National Inpatient Sample (NIS). According to these figures, our sample captured a consistent proportion of the NIS volume over time (~8%). The table also illustrates the proportion of the sample enrolled in MA over the study period and how this compares to national enrollment. Over time, the proportion of MA patients in the sample increased but at a faster rate than national trends. For this reason, we carry out all the US analysis separately for commercial insurance and MA patients.

Our data included information on patient characteristics including age, race, comorbidity, and socioeconomic status. Age and comorbidities were available in both datasets. To adjust for patient comorbidity, we used the Charlson Comorbidity Index[16] and counts of specific secondary diagnosis like diabetes, circulatory disease, respiratory disease, and mental health. Self-reported race/ethnicity was reported in the HES data, while the OLDW includes third-party race/ethnicity data estimated using individual's name and geographic location. Different measures of socioeconomic status were available in the two datasets. HES data reported values of the Index of Multiple Deprivation (IMD) for each patient, assigned based on the patient postcode. The IMD measures relative levels of deprivation in 32,844 small areas in England. Each area is allocated an IMD quintile according to the proportion income deprivation, with the first decile indicating the most deprived areas.[17] OLDW includes household yearly income estimated from a third-party model using both public and private consumer data (credit card statements and loans). This variable was assigned at the household level, where all individuals within the same household would be assigned the same income value (<40,000; 40,000–74,900; 75,000–124,900; 125,000–199,900; and >200,000). As variables on race/ethnicity and income were not directly comparable, we only used them in the sensitivity analysis.

The OLDW data also contained information on the reimbursement. In England, NHS providers are reimbursed a fixed price corresponding to an assigned health-related group (HRG), which is allocated to all hospitalized patients based on their procedure, diagnosis, age, and level of complication. HRGs are linked to fixed tariffs, which are derived from average hospital costs and are updated annually.[18] Using each patient's assigned HRG code, we identified the reimbursement rate, which was converted to 2017 US dollars using the OECD AIC Purchasing Power Parity index (Appendix Table A3).

We also extracted data on a range of surgical outcomes: LoS, 30-day readmission, and the number of urology follow-up visits within a year after surgery. We included follow-up visits as a proxy for unresolved complications that might arise postsurgery requiring further visits to a specialist.

2.2 | Methods

First, we compared the relative adoption of different approaches for prostatectomy over time by constructing a longitudinal panel for each country. We plotted the total volume of each procedure over the period 2005–2017, looking at minimally invasive approaches and also laparoscopic and robotic-assisted approaches, separately. Next, we plotted the number of hospitals performing each procedure, each year.

Second, we explored the characteristics of patients receiving each of the procedures, and their surgical outcomes, including LoS, 30-day readmission rates, and the number of urology follow-up visits between 2005 and 2017. For the United States, we explored the characteristics separately for the commercial and MA populations. To determine whether certain patients are more likely to receive a specific procedure, we also ran a multivariate regression with type of surgery as the dependent variable and age, sex, and comorbidity as independent variables.

Finally, we examined the relationship between adoption patterns and the three surgical outcomes. To examine this relationship, we used a multivariate patient-level linear regression model run separately for the commercial and MA patients (Equation 1), controlling for age and comorbidity, with hospital fixed-effects and time trends. Although the outcomes were discrete and binary, we chose linear models to preserve the interpretability of linear trends.

$$Y_{ijt} = \alpha + \beta\, surgery_{ijt} + \gamma X_{ijt} + H_j + T_t + \mu_{ijt} \tag{1}$$

Y_{ijt} indicates each outcome, for patient i, treated in hospital j in year t (2005–2017); $surgery_{ijt}$ denotes a set of binary variables indicating whether the surgical approach was open, laparoscopic, or robotic; X_{ijt} is a vector of covariates (Charlson Comorbidity Index and age); H_j denotes hospital fixed-effects; T_t is a linear time trend; $\alpha, \beta,$ and γ are unknown parameters; and μ_{ijt} is the normally distributed disturbance term. In our sensitivity analyses, we present the results using (1) individual comorbidities variables instead of the Charlson Comorbidity

Index, (2) an extended set of covariates (including race and socioeconomic status), and (3) using Poisson and Logit models.

Statistical analysis was conducted using *Stata* 15 (College Station, TX, USA).

3 | RESULTS

Our sample comprised of 66,879 patients in England and 79,358 patients in the United States who underwent a radical prostatectomy between 2005 and 2017 (Table A2). In 2017, there were 7705 patients in England and 7124 in the United States (60.8% commercial and 39.2% MA) (Table 1). In 2017, the United States performed a higher proportion of open and laparoscopic surgeries, while England had a higher proportion of robotic surgeries. In England, 91.5% of patients underwent a minimally invasive procedure, with robotic techniques accounting for 85.1% of the total. In the United States, 88.7% of commercial patients and 83.9% of MA patients had a minimally invasive procedure, of which 78.1% and 62% of the total had a robotic procedure, respectively. Prostatectomy patients were treated in 59 hospitals in England compared to 1297 in the United States. On average, across countries, the patients had a similar age (around 64 years). A higher proportion of English patients were white. Patient comorbidity as measured by the Charlson Comorbidity Index was similar across the two countries. When disaggregating by disease group, however, we observed a higher proportion of patients in all comorbidity categories in the United States compared to England. In England, most patients belonged to the less deprived category, while in the United States, most patients belonged in the middle-income

TABLE 1 Sample characteristics for England and the United States (2017)

Patient characteristics	England	United States	
		COM	MA
No. of patients	7705	4333 (60.8%)	2791 (39.2%)
No. of hospitals[a]	59	971	855
Open	656 (8.5%)	491 (11.3%)	449 (16.1%)
Minimal invasive	7049 (91.5%)	3842 (88.7%)	2342 (83.9%)
Laparoscopic	489 (6.4%)	406 (9.9%)	597 (21.7%)
Robotic	6560 (85.1%)	3198 (78.1%)	1703 (62.0%)
Age in years, mean (SD)	64 (7)	61 (7)	71 (6)
Race (%)			
White	5077 (92.1%)	2492 (79.5%)	1885 (71.6%)
Black	233 (4.2%)	296 (9.5%)	388 (14.7%)
Other	201 (3.7%)	344 (11.0%)	362 (13.7%)
Comorbidity (%)			
Charlson Comorbidity Index (mean)	2.37	2.45	2.64
Diabetes	622 (8.1%)	633 (14.6%)	620 (22.2%)
Circulatory disease	3114 (40.4%)	2297 (53.0%)	1876 (67.2%)
Respiratory disease	861 (11.2%)	404 (9.3%)	398 (14.3%)
Mental health	906 (11.8%)	712 (16.4%)	472 (16.9%)
Socioeconomic status (%)			
Socioeconomic status 1 (lower)	1112 (15%)	303 (10.3%)	527 (20.4%)
Socioeconomic status 2	1156 (15.7%)	598 (20.3%)	800 (31.0%)
Socioeconomic status 3	1285 (17.4%)	888 (30.1%)	814 (31.5%)
Socioeconomic status 4	1824 (24.7%)	638 (21.7%)	314 (12.1%)
Socioeconomic status 5 (higher)	2007 (27.2%)	517 (17.6%)	129 (5.0%)
Reimbursement (mean) (in US dollars)	$8249.24	$18,799.91	$9412.49

Note: White in the US sample represents the non-Hispanic whites (Hispanics are in others), socioeconomic status in England is represented by the Index of Multiple Deprivation and in United States is represented by household income levels (<40,000; 40,000–74,900; 75,000–124,900; 125,000–199,900; and >200,000).

Abbreviations: COM, commercial; MA, Medicare advantage.

[a]US hospitals treated both type of enrolled patients (commercial and MA) being the total number of hospitals 1297. The proportion of laparoscopic and robotic do not sum up to the proportion of minimally invasive because the CPT was missing and we could not differentiate between laparoscopic and robotic.

category (75,000–124,900). The mean reimbursement for radical prostatectomy for 2017 was $8249.24 in England, $18,799.91 for commercial patients, and $9412.49 for MA.

Appendix Table A4 shows these descriptive statistics for the baseline year, 2005. The total volume for radical prostatectomy was lower for both countries: 3257 patients in the US sample (95.9% commercial and 4.1% MA) and 4798 in England. In both, the dominant surgical technique was open prostatectomy. Minimally invasive procedures accounted for 10.3% in England and 8.5% for commercial and 4.6% for MA in the United States. A total of 120 hospitals carried out prostatectomies in England, double the 2017 number, and 1139 hospitals performed the procedure in the United States, fewer than in 2017. Patients in both countries were younger and healthier as compared to 2017. The reimbursement level was also lower in 2005, averaging $5155.94 in England, and in the United States, $11,031.56 for commercial and $7131.00 for MA.

3.1 | Volumes over time

Figure 1 shows the aggregate volumes of each procedure over time per country. In both countries, open surgery had the highest volumes until 2009 (2431 in England in 2009 and 5031 in the United States in 2008). From 2010, minimally invasive approaches overtook open approaches, reaching 7049 in England and 6184 in the United States in 2017. In both countries, this increase was driven by robotic approaches, while laparoscopic volumes were lower than both robotic and open approaches over the full period. In the late 2000s, the adoption of robotic surgery was faster in the United States compared to England, but similar levels of diffusion were reached by 2014. Appendix Figure A1 illustrates the trends for each surgical approach over time, and Figure A2 illustrates these trends separately for commercial and MA. For both groups, the overall trend was the same with open procedures dominating till 2009 after which minimally invasive took over, driven by robotic.

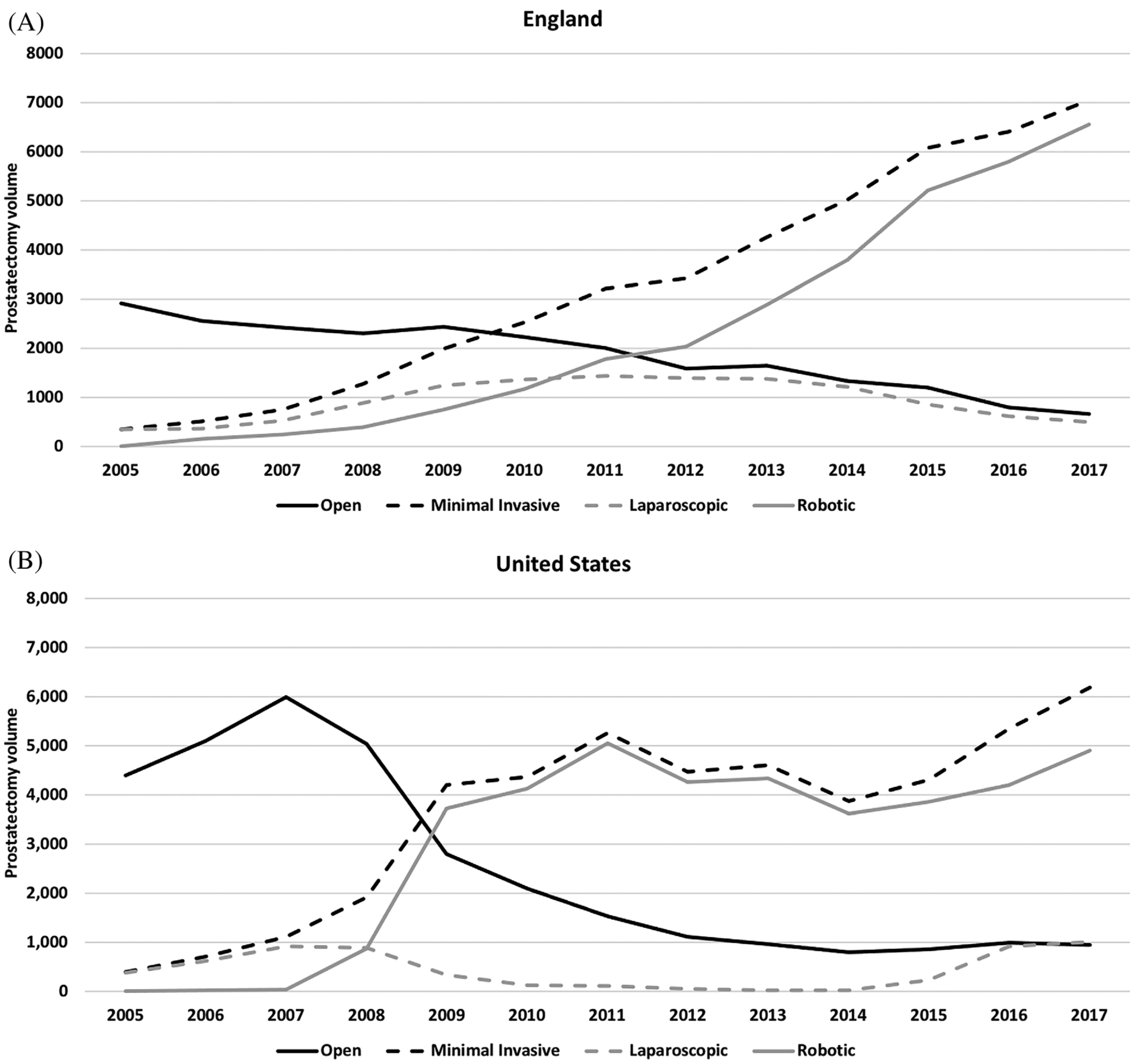

FIGURE 1 Trends for open, laparoscopic, and robotic radical prostatectomy in England and the United States (2005–2017)

Figure 2 shows the number of hospitals that performed each procedure, by year. This figure better illustrates the extent to which the increase of robotic volume is driven by small increases across all providers or large increases in a few providers. In 2005, most hospitals in both countries performed open radical prostatectomy (80% in England and 92% in the United States), followed by laparoscopic procedures (19% in England and 8% in the United States), and with almost no robotic procedures in either country. By 2017, the number of hospitals performing any prostatectomy fell in England, while it increased in the United States. Of these providers, the proportion offering open prostatectomy decreased to 48% in England and 29% in the United States. In England, the proportion of hospitals performing laparoscopic surgery in 2017 decreased to 8%, while in the United States, this increased to 13%. The total number of hospitals performing robotic surgery increased in both countries over time, representing 43% of hospitals in England and 58% in the United States by 2017.

3.2 | Changes of patient characteristics and outcomes

Over the study period, the mean age of the patients undergoing radical prostatectomy increased in both countries (Table 2). The age increase was more pronounced in the United States for laparoscopic (4.2 years commercial, 5.5 years MA vs. 1.4 years in England) and open (1.2 years commercial, 3.7 years MA vs. 2.6 years in England) approaches. The average age of patients undergoing robotic prostatectomy also increased in England (2.9 years) and the commercially insured (1.1 years), while it decreased for MA patients (1.5 years). In both countries, over time, the mean comorbidity of patients increased except for laparoscopic surgery in the United States. The largest increase in the Charlson Comorbidity Index was observed for open prostatectomy (0.4 points in England, 0.4 commercial, and 0.9 MA). In the United States, average reimbursement for open prostatectomy increased over the time period by $12,268.74 for commercial and $6774.29 for MA. Reimbursement for robotic and laparoscopic prostatectomy increased by $7364.26 and $4857.78 for commercial patients and decreased for MA patients by $2878.79 and $537.15, respectively.

Over the study period, LoS decreased for all surgical approaches in England and increased in the United States, although starting from a lower baseline. In 2017, open prostatectomy had the highest LoS for both countries (3.4 days in England, 4.4 days for commercial, and 7.1 days for MA), and robotic prostatectomy had the lowest (1.6 days in England, 2.0 for commercial, and 2.2 for MA). We observed an increase in 30-day readmissions across all three approaches, in both

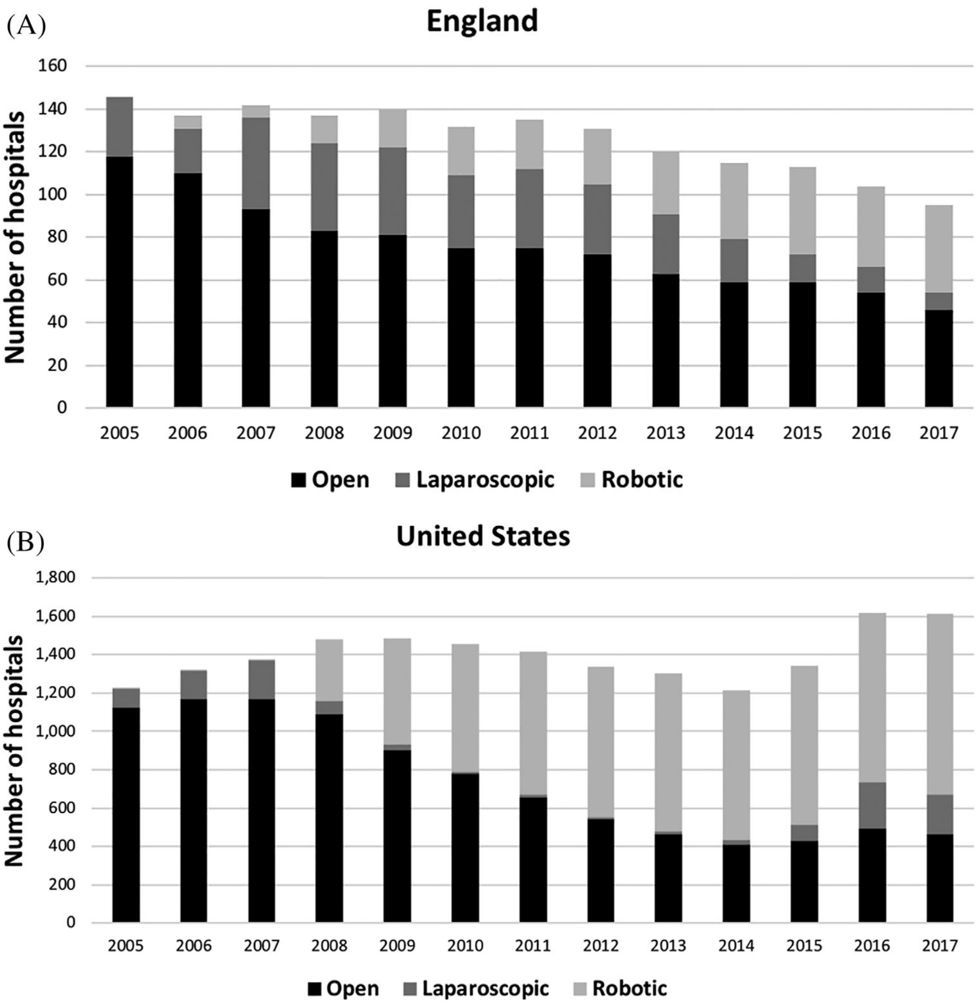

FIGURE 2 Number of hospitals performing open, laparoscopic, and robotic radical prostatectomy in England and the United States (2005–2017)

TABLE 2 Characteristics of patients undergoing open, laparoscopic, and robotic radical prostatectomy in England and the United States

		Open			Minimally invasive			Laparoscopic			Robotic		
		England	US (COM)	US (MA)	England	US (COM)	US[a] (MA)	England	US (COM)	US[a] (MA)	England	US (COM)	US[a] (MA)
Age (in years)	2005	62.2	60.4	68.7	62.4	59.7	68.8	62.4	59.7	68.8	60.7	59.2	71
	2017	64.8	61.6	72.4	63.6	60.6	70.7	63.8	63.9	74.3	63.6	60.3	69.5
Charlson Comorbidity Index	2005	2.1	2.3	2.4	2.2	2.3	2.4	2.2	2.3	2.4	2.2	2.3	2.5
	2017	2.5	2.7	3.3	2.4	2.4	2.5	2.4	2.1	2.2	2.4	2.4	2.6
Reimbursement (US dollars)	2005	–	10,983.38	6971.31	–	11,552.04	10,413.43	–	11,711.15	10,413.43	–	11,026.65	11,146.39
	2017	–	23,252.12	13,745.6	–	18,231.62	8581.6	–	16,568.93	9876.28	–	18,390.91	8267.60
Length of stay (days)	2005	6.3	2.6	2.9	4.5	1.9	1.4	4.5	1.9	1.4	3.5	1.3	2.5
	2017	3.4	4.4	7.1	1.6	2.1	2.8	2.1	3.1	4.7	1.6	2.0	2.2
30-Day readmissions (%)	2005	9.9%	4.0%	3.2%	10.4%	4.3%	22.2%	10.4%	4.3%	22.2%	9.0%	5.0%	0.0%
	2017	17.5%	12.4%	15.1%	10.8%	6.7%	6.8%	13.3%	7.9%	11.9%	10.6%	6.8%	4.8%
Follow-up urology visits (1 year) (number)	2005	1.1	3.2	3.7	1.0	2.9	3.3	1.0	2.8	3.3	1.0	2.2	3
	2017	3.5	2.8	2.7	4.0	3.0	3.4	4.7	2.6	3.1	3.9	3.0	3.5

Note: The table reports the patient characteristics' mean for each surgery type, year, and country. For robotic, the mean of 2005 is from 2006. Reimbursement for England not shown, given there is practically no variation in the tariffs used to reimburse hospitals for each procedure type.

Abbreviations: COM, commercial; MA, Medicare advantage.

[a]Number of observations for 2005/2006 are <11.

TABLE 3 Association of surgical approach with key outcomes by country, 2005–2017

	LoS			30-Day readmission			Follow-up visits		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Panel 1: Open (reference category) vs. minimally invasive									
Minimally invasive	−1.224***	−0.771***	−1.808***	−0.014***	−0.009***	−0.029***	0.204	−0.076**	0.084
	(0.119)	(0.052)	(0.289)	(0.005)	(0.003)	(0.006)	(0.134)	(0.039)	(0.077)
Age	0.014***	0.017***	0.073***	0.0003	−0.001***	0.003***	−0.017***	−0.015***	−0.013**
	(0.002)	(0.002)	(0.010)	(0.0002)	(0.0001)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.262***	0.643***	0.012***	0.022***	0.029***	0.051**	0.091***	0.002
	(0.025)	(0.020)	(0.060)	(0.002)	(0.002)	(0.002)	(0.026)	(0.015)	(0.021)
N	65,297	66,592	12,766	66,753	66,592	12,766	66,753	66,592	12,766
Hospitals	141	2436	1551	141	2436	1551	141	2436	1551
Mean outcome	3.04	2.12	2.85	10.8%	5.6%	5.7%	3.76	3.14	3.35
Panel 2: Open (reference category) vs. robotic and laparoscopic									
Robotic	−1.194***	−0.896***	−2.118***	−0.019***	−0.012***	−0.037***	−0.251	−0.069*	0.144*
	(0.160)	(0.056)	(0.268)	(0.007)	(0.003)	(0.006)	(0.231)	(0.041)	(0.083)
Laparoscopic	−1.250***	−0.269***	0.116	−0.010**	0.001	0.009	0.597***	−0.113**	−0.260**
	(0.115)	(0.068)	(0.518)	(0.005)	(0.005)	(0.011)	(0.146)	(0.057)	(0.117)
Age	0.014***	0.016***	0.047***	0.0003*	−0.001***	0.002***	−0.016***	−0.015***	−0.009
	(0.002)	(0.002)	(0.012)	(0.0002)	(0.0001)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.271***	0.666***	0.012***	0.022***	0.029***	0.050*	0.094***	−0.004
	(0.025)	(0.020)	(0.063)	(0.002)	(0.002)	(0.002)	(0.025)	(0.016)	(0.021)
N	65,297	64,649	12,597	66,753	64,649	12,597	66,753	64,649	12,597
Hospitals	141	2427	1546	141	2427	1546	141	2427	1546
Mean outcome	3.04	2.14	2.89	10.8%	5.6%	5.7%	3.76	3.14	3.34
Panel 3: Laparoscopic (reference category) vs. robotic									
Robotic	−0.261	−0.562***	−2.048***	−0.002	−0.014**	−0.049***	−0.238	0.076	0.380***
	(0.187)	(0.068)	(0.271)	(0.008)	(0.006)	(0.010)	(0.264)	(0.060)	(0.135)
Age	0.008***	0.014***	0.033***	0.0001	−0.0004**	0.002***	−0.015***	−0.014***	−0.006
	(0.001)	(0.002)	(0.001)	(0.0002)	(0.0002)	(0.001)	(0.004)	(0.003)	(0.007)
Comorbidity	0.173***	0.171***	0.534***	0.011***	0.022***	0.028***	0.052**	0.108***	0.034
	(0.029)	(0.023)	(0.057)	(0.002)	(0.002)	(0.003)	(0.025)	(0.024)	(0.030)
N	42,102	35,723	8924	42,714	35,723	8924	42,714	35,723	8924
Hospitals	81	1467	1200	81	1467	1200	81	1467	1200
Mean outcome	2.17	1.84	2.51	10.3%	5.8%	5.1%	3.76	3.10	3.36

Note: Standard errors clustered at hospital-level in parentheses. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Models adjusted for hospital-fixed effects and year trends. The period of analysis is 2005–2017 for both panels.
Abbreviations: COM, commercial; LoS, length of stay; MA, Medicare advantage.

countries. Finally, we observed an increase in the number of follow-up urology visits in both countries, apart from open prostatectomy in the United States.

To complement these trends, we report the association between surgical approach and patient characteristics over time in Table A5. In both countries, over time, open radical prostatectomy was performed on an older and more comorbid population, with minimally invasive approaches performed on increasingly younger and healthier patients.

3.3 | Surgical outcomes by type of procedure

Table 3 shows the association between hospital adoption patterns and outcomes. Minimally invasive approaches were associated with approximately a 1-day reduction in LoS relative to open prostatectomy in England and the US commercial patients. For MA patients, this reduction was nearly 2 days. Similarly, minimally invasive surgery was associated with a reduction in 30-day readmissions, of 1.4% in England, 1.0% in the commercial US sample, and 2.9% in the MA sample, relative to open surgery. When compared to open surgery, minimally invasive approaches were not significantly related to the number of follow-up visits, apart for the commercial US sample were they decreased, although by a negligible magnitude.

When we examine laparoscopic and robotic approaches compared to open prostatectomy, the reduction in LoS and readmissions is statistically significant in England. In the United States, LoS and readmission for robotic procedures declined in both commercial and MA groups. However, LoS for laparoscopic approaches only significantly decreased for the commercial patients. While there were no significant changes to follow-up visits for robotic patients in either country, we saw a significant increase in visits following laparoscopic surgery in England and a decrease in follow-up visits for both insurance groups in the United States. Older patients had higher LoS, and a lower number of follow-up visits in both countries. In the United States, older patients with commercial insurance had lower readmissions rates, while older patients with MA had higher readmission rates.

When comparing robotic versus laparoscopic outcomes, results showed no improvements of robotic approaches over laparoscopic in England. However, in the United States, the improvements were seen in LoS and 30-day readmission rates for both commercial and MA patients, although of a much greater magnitude in MA. Follow-up visits also increased for MA patients after robotic surgery, relative to laparoscopic.

3.4 | Sensitivity analysis

Table A6 used individual comorbidity variables instead of the Charlson Comorbidity Index, and results are in line with the main specification. Table A7 used an extended set of covariates including race/ethnicity and socioeconomic status, and results are also in line with the main specification. Higher socioeconomic status was associated with significantly lower LoS in both countries, lower 30-day readmissions in the United States, and more follow-up visits in the United States. Being black was related to an increase in LoS and in the number of follow-up visits for England and commercial insurance patients in the United States. Black patients were more likely to be readmitted relative to white patients in England. Table A8 estimates the coefficients using Poisson models for LoS and number of follow-up visits and Logit regression for the 30-day readmission. Results showed similar results to the main specification, but the magnitude of the effect was smaller for LoS and the number of follow-up visits and larger for 30-day readmissions (apart for MA patients where it was not significant).

4 | DISCUSSION

In this study, we explored the differential adoption of minimally invasive approaches for radical prostatectomy in England and the United States over the past 13 years. Over the study period, minimally invasive approaches, and in particular robotic prostatectomy, replaced open prostatectomy as the standard of care in both countries. The initial adoption of robotic prostatectomy was faster in the United States as compared to England, but through a more gradual adoption England reached similar levels of adoption by 2014. While rates of adoption at the end of the study period are similar at the national level, there are meaningful differences in the degree of hospital specialization within countries, which we believe is related to differences in cost-containment approaches. In both countries, over time, open radical prostatectomy is being performed on an older and more comorbid population, with minimally invasive approaches performed on the relatively younger and healthier patients. We find that minimally invasive approaches are associated with reductions in inpatient LoS and 30-day readmissions rates compared to open prostatectomy. In the United States, robotic approaches outperform laparoscopic, although this is not the case in England.

Our results raise important questions for policy makers interested in understanding the drivers and impact of diffusion of new technologies across different health systems. In this study, we observed differential adoption of minimally invasive approaches in England and the United States, with an initial faster rate of adoption in the United States. While there are many differences between the two health systems, it is likely that the differential adoption of robotic prostatectomy is related to differences in reimbursement of hospital providers, which has been observed for other types of technologies. In this paper, we examined data from two health systems as follows: the NHS, which relies on fixed prices, and a database of commercially insured and MA patients in the United States, which captures variable prices. Mostly likely as a product of these reimbursement structures, we observed large differences in the average expenditure for this procedure across the two countries, with the US spending almost consistently double the dollar amount relative to England. Interestingly, there is also a large difference in the average reimbursement between commercial insurance and MA in the United States, where commercial spending is almost double MA for all procedures. This is likely related to the need for insurance to compete with Medicare fee-for-service prices, which are lower and fixed. This raises questions about whether higher prices in commercial insurance subsidize technological adoption for the Medicare populations, or whether there are potential efficiency gains to be made in commercial insurance.

The Technological Change in Health Care Research Network[9] found the type of provider payment to be a key factor influencing the rate of adoption, particularly for new technologies with high fixed costs, where systems using fixed provider payments experienced relatively little growth in use of invasive procedures over time.[9,19] Robotic surgery has high fixed costs—the purchase of the robot and maintenance costs—which likely influences the differential adoption of the approach in the United States and England. In England, robots were purchased and used mainly for radical prostatectomy, which is among the most high-volume robotic procedure in the country. While in the United States, robots have been used across a wider range of clinical specialties,[20] which may explain the rapid uptake of the technology in the United States if providers already had robots on site. In the United States, hospitals are also likely to have funds to purchase these high-cost technologies or even to factor this into price negotiations. However, in England, NHS hospitals need the approval of the hospital's Board of Directors and the relevant Clinical Commissioning Group to purchase this technology.[21] Even with approvals granted, NHS hospitals need to raise funds to purchase the robot, which is commonly done through charities or leasing agreements.[21,22] As a result, fewer hospitals in England are able to offer robotic surgery, yet those who do offer high volumes.

Our results suggest that differential robotic adoption across hospitals not only influences volumes of robotic procedures but may also be related to the degree of procedural specialization across these two health care systems. Notably, in England, over the study period, the number of hospitals providing any type of surgery for prostatectomy halves, and nearly all prostatectomies are provided by hospitals who purchased the robotic technology and thus have the ability to offer any of the three approaches. In contrast in the United States, we observed an increase in the number of hospitals providing prostatectomies, with the increase being mostly driven by the hospitals offering robotic approaches. Comparatively, fewer hospitals continue to carry out open prostatectomy, suggesting that open approach is becoming centralized to a greater degree.

Our analysis also shows that as the robotic approach for radical prostatectomy is becoming more widespread, standard practices are changing. Over time, all three approaches are being performed on patients that are older and have more comorbid conditions. However, robotic prostatectomy is replacing open approaches, for younger and healthier patients, while open prostatectomy is reserved for more clinically frail and complex patients. While these changes in practice are observed for both countries, they are more pronounced in the United States, across both commercial insurance and MA. It is likely that as fewer hospital providers carry out open prostatectomy, and more offer robotic approaches, open surgery is reserved for a comparatively older and clinically complex population in the United States than in England where the same hospitals offer all three procedures.

Previous literature has shown that minimally invasive procedures have better surgical outcomes than open procedures.[12,13,23-25] Our results support this and show that minimally invasive procedures are associated with improvements in LoS and 30-day readmissions rates in both countries relative to open surgery. While in the United States, the improvements in LoS and 30-day readmission rates were driven by robotic surgery, in England, the differences are quantitatively similar for both laparoscopic and robotic surgery, compared to open procedures. When we compared the same outcomes between robotic and laparoscopic approaches, we found that robotic procedures are associated with improvements in LoS and readmissions, although only for the United States.

To the best of our knowledge, this is the first paper that provides a comparative analysis of adoption rates of minimally invasive surgery across countries. This paper contributes to two main themes of the literature. First, in the field of diffusion of medical innovation. Previous literature has shown that while medical innovation increases health care expenditure, it also shows improvements in surgical outcomes and quality of life.[1-6,8,9] Our results are in line with this research, as robotic surgery has a high initial investment, but it comes with centralization of care and efficiency gains. Furthermore, we compared the adoption rates of robotic surgery of two countries, showing that fixed or variable prices may influence the rates of adoption. Second, we also contributed to the specific literature on robotic surgery improvement in outcomes. Our results are in line with previous literature showing that robotic approaches are associated with better surgical outcomes than open procedures.[12,13] We also find that in the United States, robotic surgery is associated with improved outcomes compared to laparoscopic approaches.

Our study had several limitations. First, for the United States, we relied on the OLDW de-identified administrative claims data, only captures the enrolled individuals, thus will not capture the total volume of procedures performed by individual hospitals or surgeons. However, the OLDW database represents a diverse mixture of ages, ethnicities, and geographical regions across the United States, which has been shown to be similar to that of the national population.[15] To account for possible changes in the national representativeness of the MA population, we stratified all analysis and report results for this population separately. For England, representativeness was less of a concern as the data included all patients admitted for radical prostatectomy in the NHS (only 10% of the English population has supplemental private insurance[26]). Second, although the study does not claim causality, the trends and associations shown are relevant to explain the uptake of this new technology. Third, there were missing values in some of the patient-level characteristics, which reduced the sample size. We ran additional models in the sensitivity analysis, with very similar results to our base specification. Fourth, we did not have access to additional outcome data including oncologic outcomes, complications, quality of life, and overall survival, which are relevant to this population. Finally, for the United States, we did not have access to individual provider or hospital characteristics, so we were unable to control for these. We used hospital fixed-effects to try to account for these characteristics as much as possible.

Over the past 13 years, the robotic approach has become the standard of care for radical prostatectomy in both England and the United States. The adoption rates and, as a result, the observed centralization of volume have been different across countries, likely a product of differences in cost containment efforts within the two systems. Although we showed evidence of improvements in surgical outcomes associated with the robotic procedure, the differences in diffusion and specialization across the two countries suggest that these may translate into variable effects on surgical practice and hospital outcomes that become more pronounced over time.

ACKNOWLEDGMENTS

This paper was produced using HES provided by NHS Digital under Data Sharing Agreement NIC-354497-V2J9P and using the OptumLabs Data Warehouse (OLDW). The OLDW contains de-identified retrospective administrative claims data, including medical and pharmacy claims and eligibility information as well as electronic

health record (EHR) data. This paper has been screened to ensure no confidential information is revealed.

CONFLICT OF INTEREST

All authors declare no competing interests.

AUTHOR CONTRIBUTIONS

All authors conceived the study. Laia Maynou and Irene Papanicolas developed the methodological approach and wrote the first draft of the manuscript. Laia Maynou accessed the data and did the analysis. Winta T. Mehtsun and Victoria Serra-Sastre did the literature review. All authors contributed to interpretation of the data and critical revision of the manuscript and approved the final version.

DATA AVAILABILITY STATEMENT

Retrospective, de-identified administrative data were obtained from Hospital Episode Statistics provided by NHS Digital under Data Sharing Agreement NIC-354497-V2J9P and from OptumLabs® Data Warehouse (OLDW). The OLDW contains de-identified retrospective administrative claims data including medical and pharmacy claims and eligibility information as well as electronic health record (EHR). Data were provided under a data sharing agreement which prohibits onward sharing.

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How to cite this article: Maynou L, Mehtsun WT, Serra-Sastre V, Papanicolas I. Patterns of adoption of robotic radical prostatectomy in the United States and England. *Health Serv Res*. 2021;56(Suppl. 3):1441-1461. https://doi.org/10.1111/1475-6773.13706

APPENDIX A.

TABLE A1 Radical prostatectomy codes England and United States

	England	United States		
	OPCS4	ICD9-PCS	ICD10-PCS	CPT
Open	M61	60.5	0VT00ZZ	55,840
	M62	60.6	0VT07ZZ	55,842
	M64			55,845
Laparoscopic	above +Y75.1	above +54.21	0VT04ZZ	55,866
	or +Y75.2		0VT08ZZ	
	or +Y75.5			
Robotic	above (open) +Y74.3	above (open) +17.4	above +8E0W4CZ	above +S2900
	or +Y75.3		or +8E0W7CZ	
	or +Y76.5		or +8E0WXCZ	
			or +8E0W0CZ	
			or +8E0W3CZ	
			or +8E0W8CZ	

Abbreviations: CPT, Current Procedural Terminology; ICD, International Classification of Diseases; OPCS-4, Office of Population Censuses and Surveys Classification of Interventions and Procedures; PCS, Procedure Coding System.

TABLE A2 The US radical prostatectomy volumes, comparison National Inpatient Sample and OptumLabs Data Warehouse, 2005–2017

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Prostatectomies (NIS)	57,452	67,782	82,235	89,311	80,903	72,818	83,941	64,835	61,310	58,290	n/a	81,425	85,490
Prostatectomies (OLDW)	4798	5808	7108	6953	6994	6462	6800	5581	5570	4670	5154	6336	7124
Prop. Prostatectomies OLDW/NIS	8.4%	8.6%	8.6%	7.8%	8.6%	8.9%	8.1%	8.6%	9.1%	8.0%	n/a	7.8%	8.3%
Prostatectomies (OLDW – COM)	4602	5546	6689	6458	6273	5602	5804	4657	4559	3814	3965	4290	4333
Prostatectomies (OLDW – MA)	196	262	419	495	721	860	996	924	1011	856	1189	2046	2791
Prop. enrolment MA (National – Kaiser Family Foundation)	13%	16%	19%	22%	23%	24%	25%	27%	28%	30%	31%	31%	33%
Prop. enrolment in MA (OLDW – Prostatectomy)	4.1%	4.5%	5.9%	7.1%	10.3%	13.3%	14.7%	16.6%	18.2%	18.3%	23.1%	32.3%	39.2%

Note: Data sources: National Inpatient Sample (https://www.hcup-us.ahrq.gov/nisoverview.jsp), OptumLabs Data Warehouse, and Kaiser Family Foundation (https://www.kff.org/medicare/fact-sheet/medicare-advantage/). The codes to identify prostatectomies in both NIS and OLDW are the ones described in Table A1. For 2015, NIS is not reporting the volume as there was a change from ICD9-PCS to ICD10-PCS in October 2015.

Abbreviations: COM, commercial insurance; MA, Medicare advantage; NIS, National Inpatient Sample; OLDW, OptumLabs Data Warehouse.

TABLE A3 Reimbursement tariffs HRG England

HRG code	Code description	HRG tariff 2018/2019 (US dollars)
LB21A	Major open, prostate or bladder neck procedures (male), with CC score 2+	$5974.50
LB21B	Major open, prostate or bladder neck procedures (male), with CC score 0–1	$4994.63
LB22Z	Major laparoscopic prostate or bladder neck procedures (male)	$5723.49
LB69Z	Major robotic prostate or bladder neck procedures (male)	$8673.83

Note: These tariffs are for elective interventions. 99.5% of the interventions in England are elective. The CC score is the sum of all comorbidities presents. The CC splits (0–1, 2+) incorporate variations in severity and complexity within HRGs (based on diagnosis codes, procedures, age, length of stay, anatomical region, or treatment approach). Abbreviations: CC, complexity and comorbidity; HRG, health-related group.

TABLE A4 Sample characteristics for England and the United States (2005)

Patient characteristics	England	United States	
		COM	MA
No. of patients	3257	4602 (95.9%)	196 (4.1%)
No. of hospitals[a]	120	1117	103
Open	2919 (89.62%)	4210 (91.5%)	>185 (>95.4%)
Minimal invasive	338 (10.38%)	392 (8.5%)	<11 (<5.6%)
Age in years, mean (SD)	62 (6)	60 (7)	69 (4)
Race (%)			
White	2279 (92.7%)	2695 (85.1%)	143 (76.0%)
Black	102 (4.2%)	263 (8.3%)	30 (16.0%)
Other	77 (3.1%)	210 (6.6%)	>12 (>6.4%)
Comorbidity (%)			
Charlson Comorbidity Index (mean)	2.14	2.30	2.36
Diabetes	141 (4.3%)	437 (9.5%)	26 (13.3%)
Circulatory disease	774 (23.8%)	2279 (49.5%)	113 (57.7%)
Respiratory disease	188 (5.8%)	440 (9.6%)	24 (12.2%)
Mental health	26 (0.8%)	555 (12.1%)	18 (9.2%)
Socioeconomic status (%)			
Socioeconomic status 1 (lower)	417 (14.6%)	260 (12.1%)	45 (30.6%)
Socioeconomic status 2	458 (14.2%)	537 (24.9%)	63 (42.8%)
Socioeconomic status 3	576 (17.8%)	674 (31.3%)	27 (18.4%)
Socioeconomic status 4	833 (25.8%)	362 (16.8%)	12 (8.2%)
Socioeconomic status 5 (higher)	894 (27.7%)	322 (14.9%)	
Reimbursement (mean) (in US dollars)	$5155.94	$11,031.56	$7131.00

Note: White in the US sample represents the non-Hispanic whites (Hispanics are in others), socioeconomic status in England is represented by the Index of Multiple Deprivation, and in United States is represented by household income levels (<40,000; 40,000–74,900; 75,000–124,900; 125,000–199,900; and >200,000).

Abbreviations: COM, commercial; MA, Medicare advantage.

[a]US hospitals treated both type of enrolled patients (commercial and MA) being the total number of hospitals 1139.

TABLE A5 Association of surgical approach with patient characteristics by country, 2005–2017

	Open		*Minimally invasive*		*Laparoscopic*		*Robotic*	
	England	*US*	*England*	*US*	*England*	*US*	*England*	*US*
Age	0.001***	0.003***	−0.002***	−0.003***	−0.001***	0.001***	−0.001**	−0.004***
	(0.0003)	(0.0002)	(0.0002)	(0.0003)	(0.0002)	(0.0002)	(0.0002)	(0.0003)
Comorbidity	0.014***	0.020***	−0.013***	−0.021***	−0.005**	−0.011***	−0.007***	−0.010***
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)
N	66,753	79,358	66,753	79,358	66,753	77,246	66,753	77,246
Hospitals	141	2713	141	2713	141	2704	141	2704
Mean outcome	36.0%	41.1%	64.0%	58.9%	18.1%	7.3%	45.9%	50.5%
	Open		*Minimally invasive*		*Laparoscopic*		*Robotic*	
	US (COM)	*US (MA)*	*US (COM)*	*US (MA)*	*US (COM)*	*US (MA)*	*US (COM)*	*US (MA)*
Age	0.002***	0.005***	−0.002***	−0.006***	0.0003*	0.008***	−0.002***	−0.014***
	(0.0003)	(0.001)	(0.0003)	(0.001)	(0.0002)	(0.001)	(0.0002)	(0.001)
Comorbidity	0.018***	0.025***	−0.018***	−0.026***	−0.009***	−0.015***	−0.009***	−0.013***
	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.004)
N	66,592	12,766	66,592	12,766	64,649	12,597	64,649	12,597
Hospitals	2436	1551	2436	1551	2427	1546	2427	1546
Mean outcome	43.4%	28.8%	56.6%	71.2%	6.6%	10.5%	48.6%	60.3%

Note: Standard errors clustered at hospital-level in parentheses. Significance levels: ***p < 0.01, **p < 0.05, *p < 0.1. Models adjusted for prostatectomy volumes per hospital/year (each surgery type), hospital-fixed effects and year trends. The period of analysis is 2005–2017 for both panels.
Abbreviations: COM, commercial insurance; MA, Medicare advantage.

TABLE A6 Sensitivity analysis: Individual comorbidities variables

	LoS			30-Day readmission			Follow-up visits		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Panel 1: Open (reference category) vs. minimally invasive									
Minimally invasive	−1.233***	−0.802***	−2.015***	−0.015***	−0.012***	−0.040***	0.202	−0.090**	0.067
	(0.121)	(0.054)	(0.288)	(0.005)	(0.003)	(0.007)	(0.134)	(0.039)	(0.075)
Age	0.012***	0.016***	0.070***	0.0003	−0.001***	0.003***	−0.018***	−0.015***	−0.014**
	(0.002)	(0.002)	(0.011)	(0.0002)	(0.0001)	(0.001)	(0.004)	(0.002)	(0.006)
Diabetes	0.245***	0.074	−0.198**	0.018***	0.016***	0.013**	0.014	0.061*	0.060
	(0.049)	(0.047)	(0.090)	(0.005)	(0.003)	(0.006)	(0.047)	(0.036)	(0.067)
Mental health	0.125***	−0.011	−0.102	0.008*	0.001	0.003	0.099	−0.090***	−0.136*
	(0.036)	(0.024)	(0.136)	(0.005)	(0.003)	(0.006)	(0.064)	(0.030)	(0.076)
Circulatory disease	0.234***	0.074***	0.117	0.009***	0.005***	−0.002	0.144***	0.002	−0.031
	(0.031)	(0.020)	(0.125)	(0.003)	(0.002)	(0.005)	(0.037)	(0.022)	(0.056)
Respiratory disease	0.556***	0.657***	1.704***	0.013***	0.013***	0.034***	0.124**	−0.014	−0.331***
	(0.056)	(0.074)	(0.169)	(0.004)	(0.003)	(0.007)	(0.054)	(0.037)	(0.071)
N	65,297	66,592	12,766	66,753	66,592	12,766	66,753	66,592	12,766
Hospitals	141	2436	1551	141	2436	1551	141	2436	1551
Mean outcome	3.04	2.12	2.85	10.8%	5.6%	5.7%	3.76	3.14	3.35
Panel 2: Open (reference category) vs. robotic and laparoscopic									
Robotic	−1.203***	−0.922***	−2.297***	−0.020***	−0.015***	−0.046***	−0.252	−0.081**	0.128
	(0.161)	(0.057)	(0.270)	(0.007)	(0.003)	(0.007)	(0.231)	(0.041)	(0.082)
Laparoscopic	−1.259***	−0.325***	−0.326	−0.011**	−0.003	−0.010	0.595***	−0.133**	−0.260**
	(0.116)	(0.068)	(0.497)	(0.005)	(0.005)	(0.011)	(0.147)	(0.057)	(0.114)
Age	0.012***	0.016***	0.047***	0.0003	−0.001***	0.002***	−0.017***	−0.015***	−0.010*
	(0.002)	(0.002)	(0.013)	(0.0002)	(0.0001)	(0.001)	(0.004)	(0.002)	(0.006)
Diabetes	0.245***	0.067	−0.231**	0.018***	0.016***	0.013**	0.009	0.685*	0.067
	(0.049)	(0.048)	(0.090)	(0.005)	(0.003)	(0.006)	(0.047)	(0.037)	(0.067)
Mental health	0.125***	−0.014	−0.109	0.008*	0.001	0.0003	0.099	−0.079**	−0.124
	(0.036)	(0.024)	(0.136)	(0.005)	(0.003)	(0.007)	(0.062)	(0.031)	(0.077)
Circulatory disease	0.234***	0.077	0.122	0.009***	0.005***	−0.003	0.142***	−0.0002	−0.032
	(0.031)	(0.019)	(0.127)	(0.003)	(0.002)	(0.005)	(0.037)	(0.023)	(0.056)
Respiratory disease	0.556***	0.676***	1.645***	0.013***	0.012***	0.033***	0.125**	0.018	−0.319***
	(0.056)	(0.075)	(0.168)	(0.004)	(0.003)	(0.007)	(0.053)	(0.037)	(0.072)
N	65,297	64,649	12,597	66,753	64,649	12,597	66,753	64,649	12,597
Hospitals	141	2427	1546	141	2427	1546	141	2427	1546
Mean outcome	3.04	2.14	2.89	10.8%	5.6%	5.7%	3.76	3.14	3.34
Panel 3: Laparoscopic (reference category) vs. robotic									
Robotic	−0.264	−0.541***	−1.849***	−0.003	−0.012**	−0.040***	−0.239	0.088	0.377***
	(0.186)	(0.067)	(0.268)	(0.008)	(0.006)	(0.010)	(0.263)	(0.060)	(0.134)
Age	0.007***	0.014***	0.034***	−0.00004	−0.001**	0.002***	−0.016***	−0.014***	−0.007
	(0.001)	(0.002)	(0.011)	(0.0002)	(0.0002)	(0.001)	(0.004)	(0.003)	(0.008)
Diabetes	0.205***	0.073	−0.135	0.013***	0.015***	0.010	0.006	0.037	0.059
	(0.045)	(0.059)	(0.096)	(0.006)	(0.004)	(0.006)	(0.055)	(0.046)	(0.081)
Mental health	0.125***	0.017	0.029	0.013**	−0.001	−0.004	0.075	−0.063	−0.119
	(0.031)	(0.030)	(0.165)	(0.006)	(0.004)	(0.007)	(0.054)	(0.043)	(0.089)
Circulatory disease	0.178***	0.064**	0.135***	0.009***	0.007***	−0.004	0.124***	−0.0001	−0.059
	(0.036)	(0.026)	(0.065)	(0.003)	(0.002)	(0.005)	(0.033)	(0.030)	(0.066)

TABLE A6 (Continued)

	LoS			30-Day readmission			Follow-up visits		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Respiratory disease	0.433***	0.589***	1.083***	0.016***	0.014***	0.028***	0.159***	−0.006	−0.232**
	(0.064)	(0.113)	(0.163)	(0.005)	(0.005)	(0.009)	(0.058)	(0.052)	(0.091)
N	42,102	35,723	8924	42,714	35,723	8924	42,714	35,723	8924
Hospitals	81	1467	1200	81	1467	1200	81	1467	1200
Mean outcome	2.17	1.84	2.51	10.3%	5.8%	5.1%	3.76	3.10	3.36

Note: Standard errors clustered at hospital-level in parentheses. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Models adjusted for hospital fixed-effects and year trends. The period of analysis is 2005–2017 for both panels.
Abbreviations: COM = commercial insurance, MA = Medicare advantage.

TABLE A7 Sensitivity analysis: race and SES covariates

	LoS			30-Day readmission			Follow-up visits		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Panel 1: Open (reference category) vs. minimally invasive									
Minimally invasive	−1.236***	−0.741***	−1.783***	−0.015***	−0.011***	−0.029***	0.115	−0.063	0.011
	(0.123)	(0.056)	(0.304)	(0.005)	(0.004)	(0.007)	(0.145)	(0.047)	(0.080)
Age	0.017***	0.014***	0.072***	0.0003	−0.0003*	0.003***	−0.019***	−0.010***	−0.016**
	(0.002)	(0.002)	(0.011)	(0.0002)	(0.0002)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.224***	0.620***	0.012***	0.024***	0.027***	0.043	0.103***	0.004
	(0.024)	(0.019)	(0.064)	(0.002)	(0.002)	(0.002)	(0.031)	(0.018)	(0.022)
SES 2	−0.019	−0.115**	−0.245**	−0.001	−0.014***	−0.013*	0.030	0.082	0.245***
	(0.033)	(0.050)	(0.117)	(0.006)	(0.005)	(0.006)	(0.052)	(0.057)	(0.084)
SES 3	0.014	−0.207***	−0.081	−0.004	−0.014***	−0.007	0.032	0.125**	0.252***
	(0.033)	(0.049)	(0.182)	(0.004)	(0.005)	(0.006)	(0.039)	(0.051)	(0.083)
SES 4	−0.101***	−0.242***	−0.503***	0.004	−0.013**	−0.014	−0.002	0.196***	0.371***
	(0.033)	(0.049)	(0.161)	(0.005)	(0.005)	(0.009)	(0.053)	(0.061)	(0.121)
SES 5	−0.163***	−0.254***	−0.481*	−0.004	−0.018***	−0.026***	0.023	0.125*	0.286**
	(0.038)	(0.052)	(0.287)	(0.005)	(0.053)	(0.010)	(0.057)	(0.065)	(0.137)
Race: black	0.541***	0.148***	0.023	0.027***	0.005	0.005	0.457***	0.156***	−0.114
	(0.080)	(0.041)	(0.157)	(0.009)	(0.005)	(0.008)	(0.133)	(0.060)	(0.094)
Race: other	0.189***	0.007	0.343	0.005	0.001	−0.004	0.140	0.113**	−0.0001
	(0.046)	(0.056)	(0.393)	(0.007)	(0.004)	(0.009)	(0.090)	(0.056)	(0.127)
N	51,123	40,671	11,823	52,352	40,671	11,823	52,352	40,671	11,823
Hospitals	141	2111	1488	141	2111	1488	141	2111	1488
Mean outcome	3.04	2.12	2.85	10.8%	5.6%	5.7%	3.76	3.14	3.35
Panel 2: Open (reference category) vs. robotic and laparoscopic									
Robotic	−1.225***	−0.854***	−2.074***	−0.018**	−0.016***	−0.036***	−0.370	−0.062	0.067
	(0.165)	(0.057)	(0.278)	(0.008)	(0.004)	(0.007)	(0.243)	(0.050)	(0.086)
Laparoscopic	−1.244***	−0.238***	0.032	−0.013**	0.008	0.008	0.513***	−0.082	−0.282**
	(0.118)	(0.072)	(0.553)	(0.005)	(0.006)	(0.011)	(0.160)	(0.068)	(0.127)
Age	0.017***	0.013***	0.047***	0.0003	−0.0004**	0.002***	−0.018***	−0.010***	−0.013**
	(0.002)	(0.002)	(0.013)	(0.0002)	(0.0002)	(0.001)	(0.003)	(0.002)	(0.006)
Comorbidity	0.217***	0.231***	0.641***	0.012***	0.024***	0.028***	0.041	0.106***	−0.001
	(0.024)	(0.020)	(0.067)	(0.002)	(0.002)	(0.002)	(0.030)	(0.019)	(0.022)
SES 2	−0.019	−0.130***	−0.228**	−0.001	−0.014***	−0.012*	0.022	0.074	0.236***
	(0.033)	(0.048)	(0.116)	(0.006)	(0.005)	(0.006)	(0.052)	(0.058)	(0.084)
SES 3	0.014	−0.206***	−0.057	−0.004	−0.014***	−0.006	0.029	0.114**	0.253***
	(0.033)	(0.048)	(0.184)	(0.004)	(0.005)	(0.006)	(0.039)	(0.051)	(0.083)
SES 4	−0.101***	−0.248***	−0.447***	0.004	−0.013**	−0.012	−0.004	0.188***	0.353***
	(0.033)	(0.048)	(0.161)	(0.006)	(0.005)	(0.009)	(0.053)	(0.063)	(0.122)
SES 5	−0.163***	−0.268***	−0.467	−0.004	−0.019***	−0.025**	0.025	0.124*	0.251*
	(0.038)	(0.052)	(0.296)	(0.005)	(0.053)	(0.010)	(0.056)	(0.066)	(0.140)
Race: black	0.541***	0.138***	−0.002	0.027***	0.005	0.004	0.454***	0.155**	−0.125
	(0.080)	(0.042)	(0.162)	(0.009)	(0.005)	(0.007)	(0.135)	(0.062)	(0.095)
Race: other	0.189***	0.011	0.362	0.005	0.001	−0.004	0.139	0.111**	−0.015
	(0.046)	(0.055)	(0.402)	(0.007)	(0.004)	(0.009)	(0.093)	(0.056)	(0.126)
N	51,123	39,400	11,666	52,352	39,400	11,666	52,352	39,400	11,666
Hospitals	141	2104	1482	141	2104	1482	141	2104	1482

TABLE A7 (Continued)

	LoS			30-Day readmission			Follow-up visits		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Mean outcome	3.04	2.14	2.89	10.8%	5.6%	5.7%	3.76	3.14	3.34
Panel 3: Laparoscopic (reference category) vs. robotic									
Robotic	−0.311*	−0.519***	−1.908***	−0.003	−0.022***	−0.045***	−0.327	0.023	0.329**
	(0.170)	(0.070)	(0.258)	(0.009)	(0.007)	(0.010)	(0.281)	(0.071)	(0.146)
Age	0.011***	0.013***	0.033***	−0.0001	−0.0003	0.002***	−0.016***	−0.009***	−0.011
	(0.002)	(0.002)	(0.010)	(0.0002)	(0.0002)	(0.001)	(0.004)	(0.003)	(0.008)
Comorbidity	0.172***	0.153***	0.515***	0.013***	0.024***	0.028***	0.043	0.117***	0.042
	(0.028)	(0.022)	(0.055)	(0.003)	(0.002)	(0.003)	(0.027)	(0.026)	(0.031)
SES 2	−0.037	−0.136**	−0.132	0.004	−0.009	−0.017**	0.027	0.136*	0.215*
	(0.035)	(0.067)	(0.110)	(0.007)	(0.007)	(0.008)	(0.057)	(0.076)	(0.104)
SES 3	0.006	−0.175***	−0.207*	0.005	−0.009	−0.010	−0.005	0.178**	0.256**
	(0.041)	(0.064)	(0.122)	(0.006)	(0.007)	(0.008)	(0.042)	(0.067)	(0.106)
SES 4	−0.046	−0.205***	−0.157	0.010	−0.006	−0.014	−0.049	0.218***	0.378**
	(0.032)	(0.070)	(0.149)	(0.008)	(0.007)	(0.011)	(0.057)	(0.076)	(0.152)
SES 5	−0.146***	−0.206***	−0.190	−0.0002	−0.014*	−0.041***	0.004	0.211**	0.251
	(0.032)	(0.072)	(0.185)	(0.006)	(0.007)	(0.010)	(0.064)	(0.088)	(0.167)
Race: black	0.365***	0.164***	−0.145	0.027***	0.001	−0.002	0.448***	0.141*	−0.139
	(0.053)	(0.057)	(0.172)	(0.009)	(0.006)	(0.009)	(0.134)	(0.076)	(0.118)
Race: other	0.100***	−0.036	−0.103	0.001	−0.001	−0.005	0.100	0.113	−0.021
	(0.043)	(0.066)	(0.135)	(0.006)	(0.006)	(0.011)	(0.090)	(0.073)	(0.142)
N	32,091	23,123	8328	32,596	23,123	8328	32,596	23,123	8328
Hospitals	81	1342	1148	81	1342	1148	81	1342	1148
Mean outcome	2.17	1.84	2.51	10.3%	5.8%	5.1%	3.76	3.10	3.36

Note: Standard errors clustered at hospital-level in parentheses. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Models adjusted for hospital-fixed effects and year trends. The period of analysis is 2005–2017 for both panels. SES refers to socio-economic status and the base category is socio-economic status equal 1 (lower income in the United States and most deprived in England). For race, the base category is white patients.

Abbreviations: COM, commercial insurance; MA, Medicare advantage.

TABLE A8 Sensitivity analysis: Poisson and Logit

	LoS (Poisson)			30-Day readmission (Logit)			Follow-up visits (Poisson)		
	England	US (COM)	US (MA)	England	US (COM)	US (MA)	England	US (COM)	US (MA)
Panel 1: Open (reference category) vs. minimally invasive									
Minimally invasive	−0.375***	−0.361***	−0.546***	−0.035***	−0.039***	−0.011	0.057	−0.025**	0.026
	(0.034)	(0.024)	(0.077)	(0.009)	(0.011)	(0.007)	(0.037)	(0.012)	(0.024)
Age	0.005***	0.008***	0.020***	0.001*	−0.002***	0.001***	−0.004***	−0.005***	−0.004**
	(0.001)	(0.001)	(0.003)	(0.0004)	(0.0001)	(0.0003)	(0.001)	(0.001)	(0.002)
Comorbidity	0.071***	0.101***	0.146***	0.026***	0.066***	0.008**	0.012**	0.030***	−0.00002
	(0.008)	(0.007)	(0.015)	(0.004)	(0.003)	(0.004)	(0.006)	(0.005)	(0.007)
N	65,286	66,000	12,250	66,589	58,336	8237	66,742	65,836	12,109
Hospitals	130	1896	1042	115	944	397	130	1847	1007
Mean outcome	3.04	2.12	2.85	5.8%	5.6%	5.7%	3.76	3.14	3.35
Panel 2: Open (reference category) vs. robotic and laparoscopic									
Robotic	−0.431***	−0.413***	−0.690***	−0.047***	−0.048***	−0.028*	−0.064	−0.022*	0.045*
	(0.052)	(0.024)	(0.065)	(0.010)	(0.012)	(0.016)	(0.062)	(0.013)	(0.026)
Laparoscopic	−0.332***	−0.124***	−0.055	−0.025**	0.002	0.002	0.159***	−0.037**	−0.077**
	(0.036)	(0.031)	(0.110)	(0.010)	(0.019)	(0.007)	(0.039)	(0.019)	(0.037)
Age	0.005***	0.007***	0.011***	0.001*	−0.002***	0.001***	−0.004***	−0.005***	−0.003
	(0.001)	(0.001)	(0.003)	(0.0004)	(0.001)	(0.0003)	(0.001)	(0.001)	(0.002)
Comorbidity	0.071***	0.101***	0.143***	0.025***	0.066***	0.015**	0.012**	0.031***	−0.002
	(0.008)	(0.007)	(0.013)	(0.004)	(0.003)	(0.008)	(0.006)	(0.005)	(0.007)
N	65,286	64,075	12,081	66,589	56,374	8092	66,742	63,894	11,940
Hospitals	130	1889	1037	115	933	395	130	1839	1002
Mean outcome	3.04	2.14	2.89	10.8%	5.6%	5.7%	3.76	3.14	3.34
Panel 3: Laparoscopic (reference category) vs. robotic									
Robotic	−0.092	−0.280***	−0.611***	−0.006	−0.055***	−0.047	−0.057	0.025	0.113***
	(0.075)	(0.031)	(0.067)	(0.015)	(0.020)	(0.037)	(0.062)	(0.019)	(0.042)
Age	0.004***	0.008***	0.011***	0.0002	−0.002**	0.002***	−0.004***	−0.005***	−0.002
	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Comorbidity	0.080***	0.080***	0.151***	0.027***	0.066***	0.024	0.012**	0.036***	0.010
	(0.011)	(0.009)	(0.012)	(0.005)	(0.004)	(0.016)	(0.006)	(0.007)	(0.009)
N	42,098	35,390	8488	42,686	30,445	4955	42,711	35,368	8376
Hospitals	77	1161	770	72	598	266	78	1149	740
Mean outcome	2.17	1.84	2.51	10.3%	5.8%	5.1%	3.76	3.10	3.36

Note: The table reports the average marginal effects. Standard errors clustered at hospital-level in parentheses. Significance levels: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Models adjusted for hospital-fixed effects and year trends. The period of analysis is 2005–2017 for both panels.

Abbreviations: COM, commercial insurance; MA, Medicare advantage.

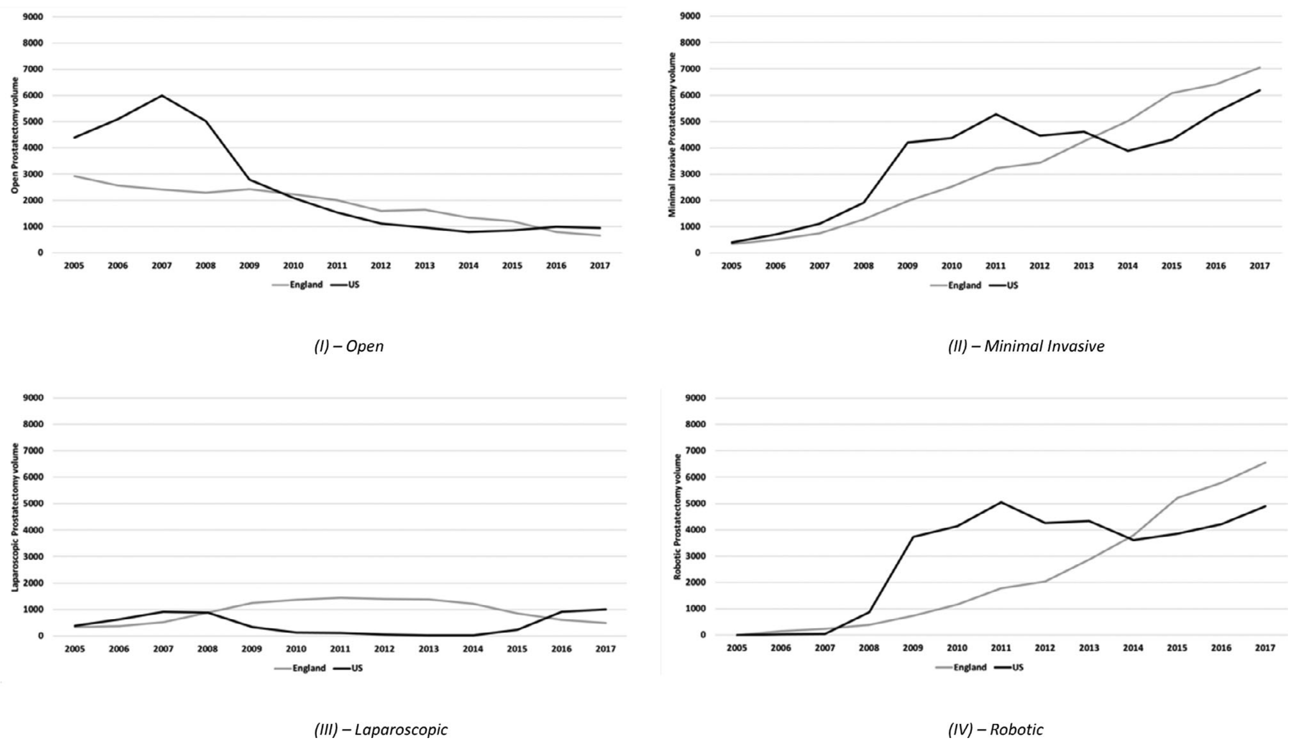

FIGURE A1 Trends of adoption in open, minimal invasive, laparoscopic, and robotic radical prostatectomy in England and the United States (2005–2017)

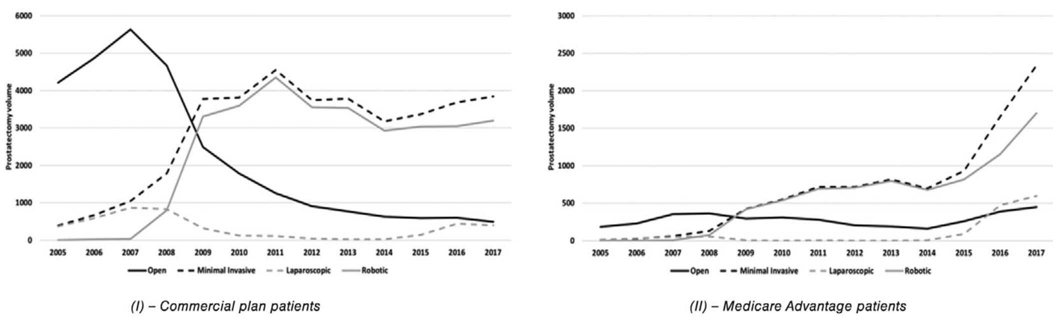

FIGURE A2 Trends of adoption in open, minimal invasive, laparoscopic, and robotic radical prostatectomy in the United States by type of patient (2005–2017)